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Energy Procedia 75 (2015) 1809 – 1818

Energy Procedia

The 7th International Conference on Applied Energy – ICAE2015

Energy Analysis of Relics Museum Buildings

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Abstract

With an increase of building energy consumption, the requirement of building energy conservation becomes a key importance of national energy development. It's not feasible to apply the traditional method to predict and analyze energy consumption in relics museums like the Emperor Qin's Terra-Cotta Warriors and Horses Museum at Xi'an City, China, due to the particularities of soil and building structures. This paper uses commercial software DeST to analyze the building energy consumption by estimating building cooling and heating loads hourly. The single factor method is used to analyze the affection of load influential factors and the average unit change value and rate method is used to analyze the factor levels. The predicted results show that the simulated building possesses considerable energy saving potential. In addition, the significance of various loading impact factors is further discussed.

Peer-review under responsibility of Applied Energy Innovation Institute

Keywords: Relics museum; Energy consumption; Energy factors

1. Introduction

Energy consumption becomes prominent with the social development, especially in buildings [1]. Building energy consumption accounts for 27.6% of total consumption, among which public buildings take a large proportion. To 2011, the public building area of China was 8 billion square meters. The public buildings took only 17% of total area but consumed 24.8% of total energy consumption, and the energy intensity peak is transferring to "large public buildings" [2]. Building energy conservation is imminent.

As an important carrier of cultural heritage, museums are requested to provide appropriate conditions of preservation and comfortable visit environment. Also, it's necessary for research and explore. Due to the different requirements of heritage preservation, the museums need strict and exactly indoor environment controls causing more energy consumptions. The consequent problem is the increasing building energy consumption against requirements for energy conservation [3].

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Peer-review under responsibility of Applied Energy Innovation Institute
doi:10.1016/j.egypro.2015.07.150

Relics museum is defined as “The specialized museums established on ancient culture site for excavation, conservation, research and display” [4]. Since the sites are part of heritage and immovability, the relics museums generally have larger building volume and energy consumption. Therefore, energy consumption and distribution in relics museum buildings must be analyzed particularly in order to provide recommendations in energy conservation.

The Emperor Qin's Terra-cotta warriors and horses Museum is a typical building of soil relics museum. Since soil has heat storage properties which makes building show different load feature, this article choose the first hall of museum for energy research.

2. Energy consumption simulation

The base of building energy simulation is thermal process simulation. For relics museum buildings, the indoor thermal conditions are affected by indoor and outdoor thermal perturbations, including outdoor heat, humidity, ventilation, radiation conditions and indoor occupants, equipment and HVAC dissipation. The soil heat dissipation and wet scatter are particular indoor factors of relics museums different from those of normal buildings. In addition to this, the mobility and the clustering coefficient of people are important to thermal environment. The building thermal process of the first hall is shown in Fig. 1.

Building energy simulation uses DeST-C simulation software developed by Tsinghua University [5]. The mathematical model consists of input parameters, system structures and output parameters. For energy simulation, the input and output parameters refer to building design parameters and heating/cooling load, respectively [6].

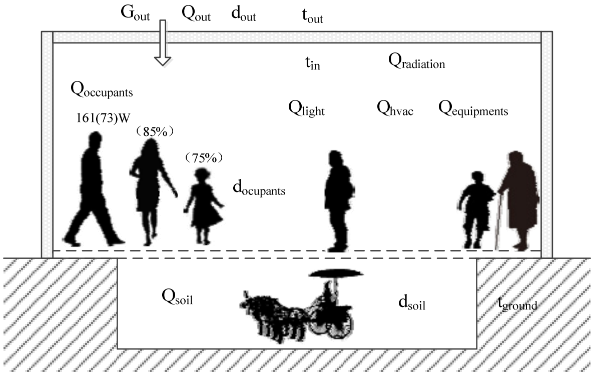
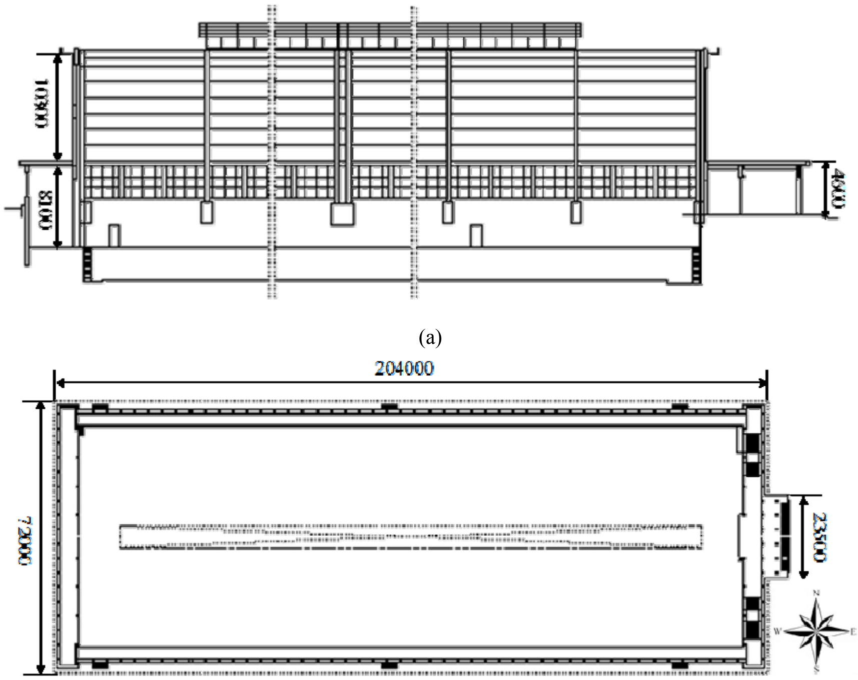


Fig. 1. The building thermal process of the first hall

2.1 Building overview

The first hall of Terra-cotta Warriors and Horses Museum was established in 1976, officially opened on October 1, 1979. The building was constructed by the arched steel structure, with 230 meters from east to west, 70 meters from south to north, 22 meters from pit bottom to hall top, and, the total construction area is about 16,000 square meters. Elevation and plan views are shown in Fig. 2. The external dimensions of building are given by the Emperor Qin's Terra-cotta warriors and horses Museum.



(a)

(b)

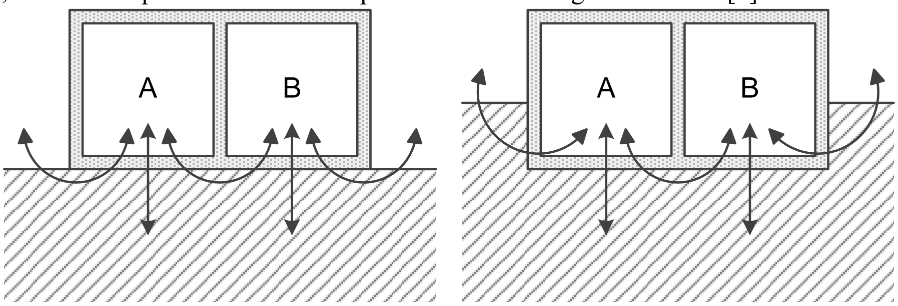
Fig. 2. The first hall of Terra-cotta Warriors and Horses Museum: (a) elevation view; (b) plan view

2.2 Building model

The parameters of building model are critical to the accuracy of calculation results. Since the semi-underground form of first hall, the whole building is stratified to ensure that model is in line with actual situation.

2.2.1 Model structure setting

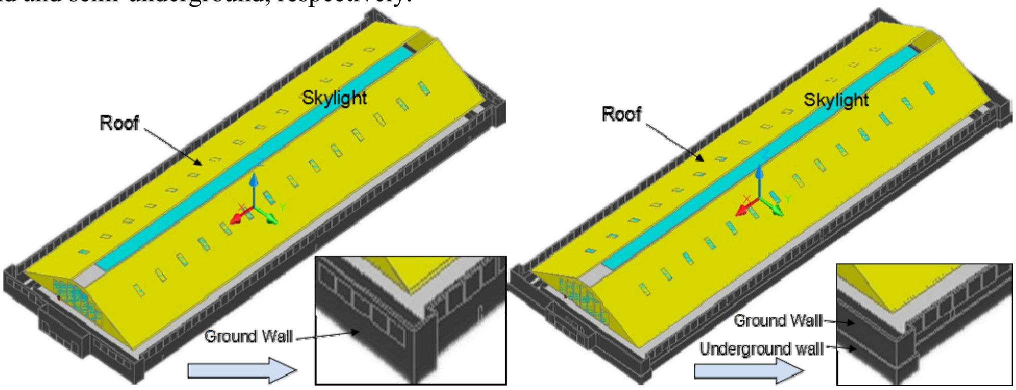
When the building is connected with the ground, two different heat exchange processes should be evaluated before the simulation, i.e., above ground and semi-ground models as shown in Fig. 3. Obviously, the thermal process is more complex for semi-underground model [7].



(a) (b)

Fig. 3. Thermal exchange process (a) above ground (b) semi-underground

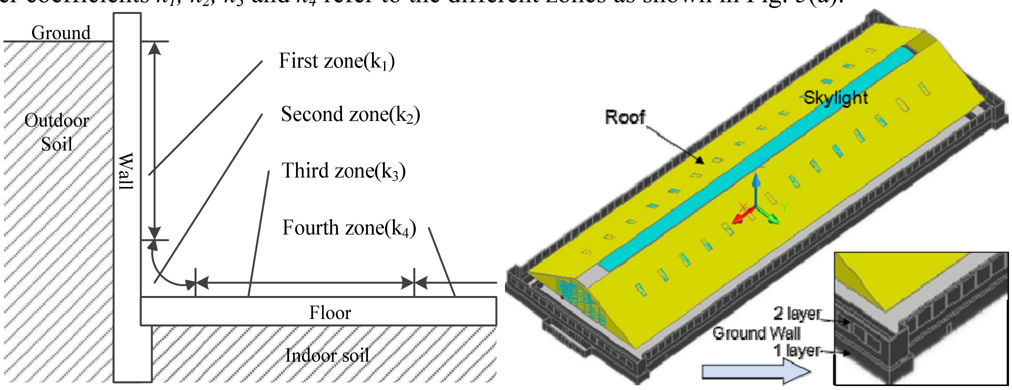
As partially underground, the indoor thermal environment of the first hall is affected by both outside air and ground soil at the same time, which raises the difficulty for modeling the structure. To evaluate the coupled effects of outside air and surrounding soil on the heating/cooling loads, two different models as shown in Fig. 4 are examined, namely, Model 1 and Model 2, referring to the building all above the ground and semi-underground, respectively.



(a) (b)

Fig. 4. Building models: (a) Model 1: all on the ground; (b) Model 2: semi-underground except pit area

The simulation results show significant disparities between the two models that Model 1consumes larger energy about 488 MW·h annually compared to that the Model 2 does. In order to mimic the actual conditions of relics museum, Model 3 with combining advantages of Model 1 and Model 2 is proposed to correct the external walls through heat transfer zone division method [8]. The various surface heat transfer coefficients k_1, k_2, k_3 and k_4 refer to the different zones as shown in Fig. 5(a).



(a) (b)

Fig. 5. (a) Zone division; (b) Model 3

According to the zone division method, the whole building is divided into four layers with the height of 2.5 m, 3 m, 5.1 m, 10.3 m (from bottom to top) for each layer. The building layers are modeled in Fig. 5(b) where the pit and visit regions refer to the underground and first ground layer respectively; and the external walls of the first ground layer are assumed to be covered by 1200 mm thick soil. All the dimensions of the building model for the simulation are set according to the actual parameters of the relics museum and mutual ventilations are added to adjacent layers as well.

2.2.2 Indoor design parameters

The whole building is set as air-conditioned area, while the visiting time for tourist is from 8:30 to 17:30, and the running time of the system is set from 8:00 to 17:00. According to the relevant provisions, the indoor temperature is designed at 26℃ in summer and 18℃ in winter, relative humidity 40~60% all year round. The indoor maximum occupant density is 0.2 $P \cdot m^{-2}$ with showroom rest pattern. Ventilation is 20 $m^3 \cdot h^{-1}$ and 8-12 times refer to ASHRAE standard [9]. Outdoor climate data of Xi'an city are originally embedded in the software.

2.3 Energy simulation results

2.3.1 Energy consumption analysis

Building energy efficiency level is determined by reference building which should meet the national stand for energy efficiency, and mainly containing the heat transfer coefficient of walls, windows and roofs. Using the numerical software (DeST-C) [10], the heating and cooling loads of the first hall and the reference building are separately calculated and demonstrated in Table 1. According to the simulation results, the total energy consumption for the first hall is about 1000 MW·h higher than that for the reference, confirming the necessity of renovation.

Table 1. Heating and cooling loads of the first hall and the reference building

Model	Maximum (kW)		Total load (MW·h)	
	Cooling	Heating	Cooling	Heating
First hall	2860.66	8559.00	850.71	2934.93
Reference	3003.74	6369.95	778.08	2001.48

In this article, the whole year heating and cooling load of every layers in first hall are calculated, and their proportion in total building load are separately shown in Fig. 6. According to the results, the maximum heating load is pit layer but the cooling load is very small, that is because the temperature of soil is continuously lower than that of air in summer, and results in the decrease of cooling load. Meanwhile, the maximum cooling load is roof layer, which is because this layer has huge volume and surface area, which can make more solar radiation enter and rise the indoor temperature, and result in the increase of cooling load.

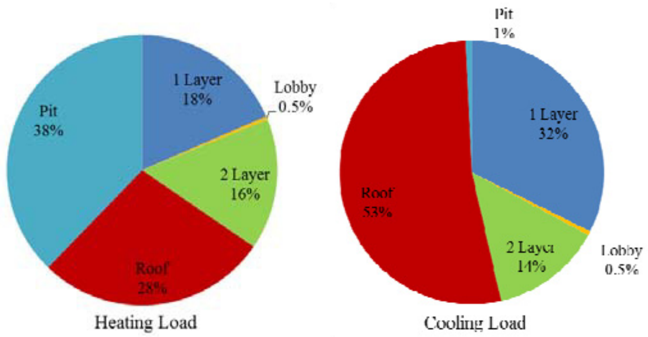


Fig. 6. Load proportion of layers

2.3.2 Solar radiation analysis

Solar radiation is an important factor of indoor thermal environment and it varies in times, regions and areas. The solar radiation intensity in Xi'an is up to 970W·m^{-2} in summer and 570W·m^{-2} in winter. Building block shadows will decrease solar radiation but translucent envelops will increase it, conversely, and then affect the indoor thermal environment. Therefore, the solar radiation analysis of the first hall is required to provide basis of energy analysis through DeST-BSHADOW module. The year round sun trajectory of first hall is shown in Fig. 7.

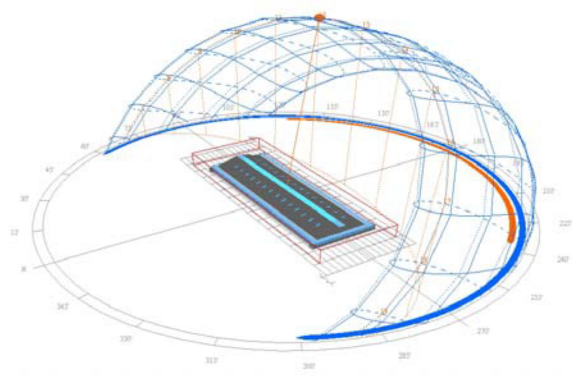
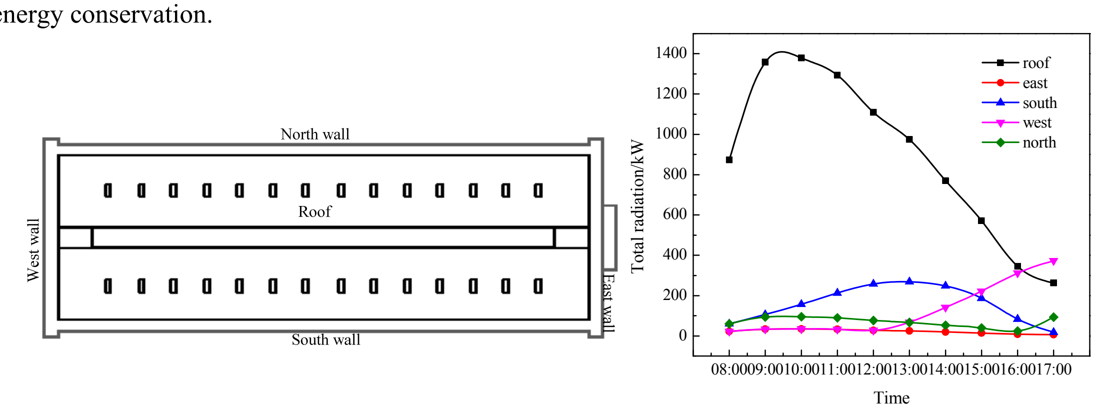


Fig.7. The year round sun trajectory of first hall

The building roof and walls of second layer are selected to calculate the building solar radiation. And the total solar radiations of eight hours in July 31 are simulated as shown in Fig. 8. The simulation results show that the roof has a highest radiation compared to the other parts, due to the huge surface area of roof and the longest time exposed to sunshine. The radiation intensity is increased in the morning, peaked at 10 a.m. and then gradually decreased. Therefore, measures of zoning control should be considered for energy conservation.



(a) (b)

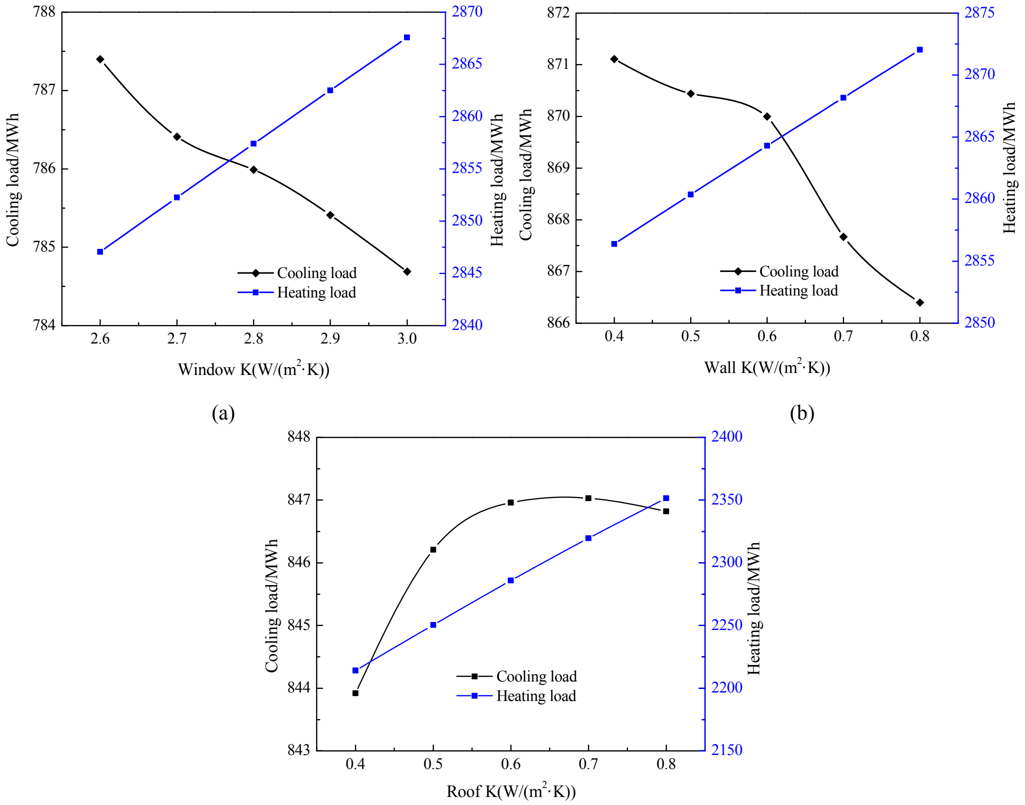
Fig. 8. Solar radiation simulation (a) The selected face; (b) Total solar radiation

3. Factor analysis

Building energy consumption includes air condition, lighting, equipment, heat loss in building envelope, etc. In order to determine the reasonable energy-saving measures, these factors need to be analyzed. In the present study, the factors are divided to two groups, i.e., envelop factors containing walls, windows and roofs, and human factors including personnel density and rest patterns. The influence of each factors upon heating/cooling load are analyzed respectively.

3.1. Envelope factors

Through changing the heat transfer coefficients of various components, the change of heating/cooling load can be obtained. The coefficients are ranged from 2.6 to 3.0$Wm^{-2}K^{-1}$ for windows, from 0.4 to 0.8 $Wm^{-2}K^{-1}$ for walls and roofs, respectively, and with an increment of 0.1 $Wm^{-2}K^{-1}$.



(c)

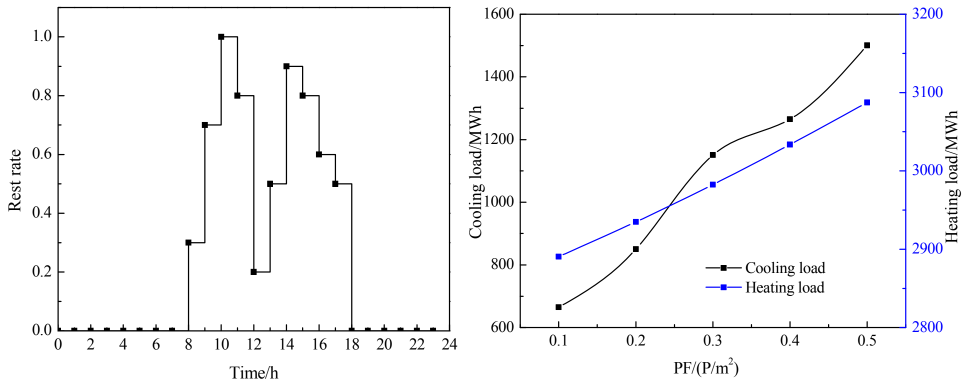
Fig. 9. Load simulation (a) window; (b) wall; (c) roof

The energy consumption of each factors are shown in Fig. 9, and the distinct trends of heating/cooling load for each factors can be observed. For windows and walls [Fig. 9(a) and (b)], cooling load decreases while heating load increases with the increase in heat transfer coefficients, but it's not significant for cooling load. When coefficients increase, heat exchange will be strengthened. Because the bigger windows area is much higher than that of walls, the indoor heat of the first hall depends mainly on radiation heat transfer. In summer night, due to the lower temperature of soil, excess heat is absorbed, and in winter, heat exchange enhances dramatically due to the significant indoor and outdoor temperature difference. These consequently result in the decreasing need for cooling load in summer and the increasing need for heating load in winter.

For roofs [Fig. 9(c)], heating load increases gradually with the increase in heat transfer coefficient, while cooling load increases firstly then decreases slightly with the increase in heat transfer coefficient. This is attributed to the huge roof area of the building where solar radiation in summer is higher than that of traditional buildings. When heat transfer coefficient increases, the temperature rises quickly and then approach to a constant value in summer.

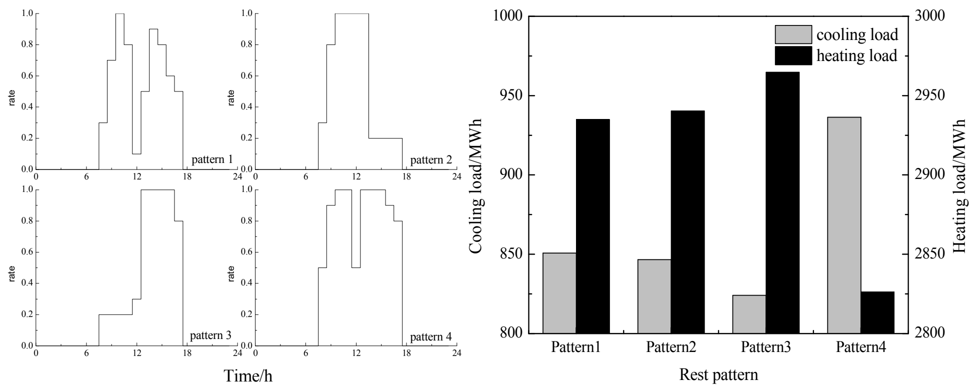
3.2. Human factors

In this article, the influence on heating/cooling load of visitors is simulated by changing the maximum personnel density of model, with the default showroom rest pattern. The values of personnel density are ranged in 0.1~0.5 Pm^{-2} and increased by 0.1 Pm^{-2}. The increasing trends of cooling and heating loads with the increase of personnel density are shown in Fig 10. The results validate that the larger amount of person, the more energy needs to be provided.



(a) (b)

Fig. 10. (a) rest pattern; (b) load simulation



(a) (b)

Fig. 11. Visitor distribution simulation (a) four rest patterns; (b) load simulation

For museums, visitor distribution varies in different times, and even at the same time, it is affected by holidays and tourist seasons [11]. This article picks four different rest patterns to evaluate the influence of visitor distribution as shown in Fig. 11. The results show that the whole year heating and cooling loads differ in four patterns, in which the pattern 3 has highest heating load and lowest cooling load, while pattern 4 exhibits the opposite trends. This is because when system starts working in summer, the indoor temperature reduces quickly and then the need for cooling load decreases, which means the higher cooling load in preliminary stage. While for winter, the heat dissipation of human takes a large proportion of heating load. The less of visitors and low temperature in winter will lead more heating load.

3.3. Factor level

In order to determine the specific impact of factors on energy consumption, the average unit change value and rate are used to measure the factor levels. In this article, the heating loads of the four factors are compared as shown in Table. 2. The data show that the most influential factor is personnel density, and the second one is roofs. While the influences of windows and walls are not obvious for this building. These confirm the importance of human load control. In addition, proper techniques should be taken to reduce the energy consumption by roofs.

Table.2. Factor levels

Factor	average unit change value (MW·h)	average unit change rate
Window	51.6	1.81%
Wall	39.4	1.38%
Roof	354.5	16.0%
PF	2092.5	315%

Conclusion

The present study hourly simulates the energy consumption of the first hall of the Emper Qin's Terra-cotta Warriors and Horses Museum. The results show that a energy (~1000 MW·h per year) consumed by the relics museum is much higher than that by a reference building with the standard energy consumption, revealing a considerable potential for energy conservation. The maximum proportion in the total heating load is the pit layer possessing as 38% and in the total cooling load does the roof layer possessing as 53%. Furthermore, the influential factors (the heat transfer coefficient of roofs, windows, walls and the personnel density) upon heating/cooling load are both analyzed. For windows and walls, cooling loads decrease but heating loads increase with the increase in heat transfer coefficient. While for roofs, heating load increases while cooling load increases firstly then decreases slightly with the increase in heat transfer coefficient. For human factors, heating and cooling load both increase with the increase in personnel density and differ in visitor distributions. Among these factors, personnel density is the most critical factor.

Acknowledgments

This study is supported by the National Science and Technology Ministry of China (under Grant No.2012BKA14B010).

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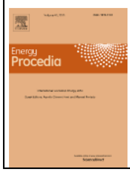

Biography

Dr. Meng Xiangzhao obtained his Master and Ph.D. degrees from Xi'an Jiaotong University, China. His research interests include the building environment measuring technology, evaluation of building energy consumption and experimental heat transfer.